

# Real-time Command, Data and Control Concepts for the Instrument on the Space Interferometry Mission<sup>1</sup>

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## Abstract

The Space Interferometry Mission (SIM), slated to launch in 2008, will require simultaneous operation of tens of control loops running at kiloHertz rates. The task of designing a computer control system to run this complex, distributed system will require careful requirements analysis and design flow. Though the project is in early phases, the process to flow the flight system command, data, and control system requirements to the instrument real-time control design is well along. In this paper we give a glimpse into the process and resulting design.

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## 1 Introduction

The Space Interferometry Mission (SIM) is slated to launch in 2008. The SIM Flight System is shown in Figure 1. The figure shows seven siderostat bays housed in the precision structure, the metrology boom with attached kite, solar panels and the high-gain antenna. Below the precision structure are the two backpacks which house the spacecraft avionics and instrument electronics. SIM is described in some detail in [1].

The purpose of the SIM Flight System is to (1) provide precision relative stellar angular measurements, (2) demonstrate the capability of interferometers for imaging, and (3) demonstrate interferometric nulling, all in the visible spectrum. Items (2) and (3) are technology demonstrations for SIM. Item (1), measuring angles of stars precisely, is the main focus for SIM and, for example, will allow scientists to generate detailed maps of the Milky Way galaxy. A Michelson stellar interferometer, like that used on SIM, allows one to make accurate angular measurements of stars provided that the baseline vector (in "star space") and the starlight pathlength difference from the CCD pixels to the endpoints (or fiducials) defining the baseline can be accurately determined. On SIM these quantities must be derived from knowledge of distances on the order of picometers. The Flight System is required to make repeatable metrology and fringe measurements at the sub-nanometer level in order to meet this goal.

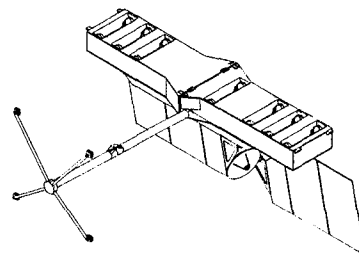


Figure 1. SIM Flight System

The basic hardware components of interferometers are the siderostats, steering mirrors, delay line and beam combiner. The siderostats are steerable flat mirrors that direct starlight down the optical axes that comprise the arms of the interferometer. On SIM, the siderostats

<sup>1</sup> 0-7803-6599-2/01/\$10.00 © 2001 IEEE

have corner-cubes mounted on their surfaces that provide the means for defining the fiducials of the interferometer. Articulated stirring mirrors, or fast steering mirrors, provide fine control of the light beams that are transmitted from the siderostat mirrors, through the delay lines and to the beam combiner. The delay lines, one passive and one active for each interferometer, provide the means to accurately control the difference in pathlength that the starlight travels through each arm to reach the beam combiner. The beam combiner combines the starlight from the two arms to produce a measurable fringe on CCD pixels.

The SIM Flight System provides seven siderostats, with accompanying steering mirrors, and four beam combiners, with accompanying delay lines. An optical switchyard allows simultaneous operation of three interferometers with the capability to route starlight from any pair of siderostats to any beam combiner. There is one spare siderostat and one spare beam combiner for redundancy. The reason for operating three interferometers will be explained shortly.

In order to measure changes in the interferometer baseline absolute lengths and relative orientations accurately, the Flight System is equipped with a metrology system. This system measures the pathlength of laser light from each of the corner cubes attached to the siderostats to a common set of four corner-cubes on the kite. This set of measurements provides information to compute the position of all the corner-cubes in a common (flight system fixed) frame. Thus, the metrology system provides the capability to measure the lengths of the baselines accurately as well as the relative orientations of the baselines. However, the metrology system does not provide the capability to track changes in any baseline orientation in inertial space. This takes more work.

With the SIM Flight System at a fixed inertial attitude, the system provides the capability for any of its interferometers to observe any sufficiently bright star within a fifteen-degree field of regard. While SIM is pointed at a fixed attitude, two of its interferometers, acting as *guide interferometers*, will be locked onto two guide stars. This provides the capability to track relative changes in the baselines in inertial space.

The SIM Flight System requires a high precision attitude control system (ACS) to provide precision spacecraft attitude control. Slews and precision pointing are accomplished under the control of six reaction wheels. The spacecraft is equipped with a high-gain antenna operated in XBAND and a solar array which provides over 4000 watts of power. The antenna and solar array are both articulated to provide minimum pointing constraints on the Flight System. There is a sun exclusion zone of  $\pm 30$  degrees from the center of the instrument field of regard.

The SIM Flight System is composed of the Spacecraft Subsystem (SCS), the Real-time Control Subsystem

(RTC), the Starlight Subsystem (STL) and the Metrology Subsystem (MET). Operation of the Flight System will be controlled primarily on computers operating within the Spacecraft and Real-time Control subsystems. The SCS and RTC subsystems will communicate over a common data bus such as MIL-STD 1553b. The SPC is equipped with a 48Gb solid state recorder. The RTC has 512 MB of volatile memory and 512 MB of non-volatile memory. For a more complete description of the instrument electronics see [2].

The instrument on SIM is a complex system with tens of control loops, over a hundred actuators and sensors, and hundreds of electronics boards. It is important in designing a system of this complexity to do careful top-down analysis of its operation. In this paper we show a glimpse into the analysis design flow that is being done to insure a properly working system is developed for flight. In Section 2 we provide a brief description of the instrument RTC subsystem. In Section 3 we provide a top-level use case for the instrument and in Section 4 describe the control architecture for the system.

## 2 An Instrument Use Scenario

The job of the ground operators is to provide sequences to operate the flight system and the job of the flight system is to implement the functions called out in the sequences. The process of developing sequences, or use-cases, early in the project allows the operators and system designers to agree on a set of functions to be provided by the flight system. In the following scenario we will explore some of the functions to be performed by the flight system and the following sections will explore the preliminary design implied by these functions.

The scenario we choose to explore is that of getting fringe measurements for a set of stars at a specific spacecraft attitude. The science team will provide a list of target stars for observing. The science operations team will add to the list several grid star observations. The grid star observations provide a reference grid for generating a global map of the sky.

Once this is done the uploaded sequence is delivered. This may include the following:

1. Instrument reconfiguration. This function will specify which elements of the instrument will be grouped to establish the required three interferometers.
2. Instrument calibration. After each reconfiguration, some level of calibration may be required. The sequence will call out specific calibrations to be performed.
3. Tile observation. This function will get the spacecraft pointed to the correct attitude, acquire guide stars and iterate through the list of science stars. At the end of this time the required science

data will be stored in the spacecraft solid-state recorder (SSR), ready for download.

The Flight System Operations Team has worked with scientists, spacecraft engineers, instrument engineers, ground system engineers and operators to define a set of baseline use cases. The use-cases have been analyzed and carried to the RTC subsystem, where the direct user, or actor, is the Spacecraft Subsystem.

## 2.1 Instrument Configuration

Configuration of the instrument is based on the following defining principles. These will be used to drive requirements on the associated RTC flight software. In the description below an IFC is an Instrument Flight Computer. The current SIM baseline provides four IFCs.

The Instrument is *configured for one science baseline* if

- the instrument is configured for external metrology
- two sidbays and one combiner-IFC pair are configured to operate as a guide interferometer, named Guide Interferometer 1
- two sidbays and one combiner-IFC pair are configured to operate as a guide interferometer, named Guide Interferometer 2
- two sidbays and one combiner-IFC pair are configured to operate as a science interferometer, named Science Interferometer 1
- the instrument is calibrated for baseline estimation, the three interferometers (two guide and one science) are calibrated

The Instrument is *configured for external metrology* if

- one or more IFC is executing the External Metrology Function
- the instrument interconnect (the interface between the IFCs and the remote actuators/sensor cages) is configured to allow the above IFC to sample all available external metrology sensors (phasemeters)
- the IFC is receiving metrology data at the nominal rate (e.g., 1000/sec)

A *guide interferometer* is *configured* if

- the instrument interconnect is configured to route data from two specified siderostat bays to a specified IFC
- the software in the IFC is configured to run all control servos associated with a guide interferometer

Figure 2 illustrates how siderostat bays are paired with combiners to create three operating interferometers.

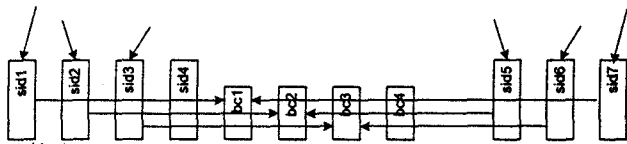


Figure 2. Instrument Configuration

The command sequence will explicitly call out the above configuration information prior to any observations.

## 2.2 Tile Observation

A tile observation is the nominal sequence for gathering science data. This sequence requires the following conditions to be satisfied to start:

1. The Instrument is configured for one science baseline (as defined above).
2. The Instrument is calibrated for science. This has not yet been explicitly defined in the project to date.
3. The spacecraft is capable of precision pointing.

Before starting the observation sequence the Instrument will insure the above conditions are satisfied.

Figure 6 in the Appendix shows an activity diagram for the following sequence of operations. Each line of action in the figure represents, essentially, one concurrent task in the software.

The sequence will start with the Instrument requesting a spacecraft slew to the target tile attitude. While the spacecraft is slewing, the Instrument will have the opportunity to point (without starlight sensors) siderostat mirrors and position delay lines.

The next step in the sequence is to acquire pointing in the guide interferometer siderostats. This requires acquisition and tracking algorithms to lock onto guide stars in each of the four guide siderostats. Once pointing in the guide siderostats is accomplished, the guide interferometers will be able to acquire and track fringes. The control system must be able to keep the central fringe stable (in the CCD frame) to less than 10 nanometers, 1-sigma.

When the guide siderostats are tracking the guide stars, there will be sufficient angle feedforward information (see [1]) to aid in acquiring and tracking a (dim) science star. Once the guide fringe interferometers are tracking fringes, the science interferometer fringe acquisition and tracking can be accomplished.

When all interferometers are tracking, the fringe tracking data is recorded for the specified amount of time. When the time is exceeded, the next science star sequence starts. Dim star pointing is acquired, followed by fringe acquisition and tracking. The process repeats (as shown in Figure 6) until all stars in the list are process or until a timeout is hit.

## 3 Control Architecture

Based on the architecture of the system and the requirements illustrated by the activity diagram, the control architecture was partitioned into Instrument and Interferometer levels as illustrated in Figure 3.

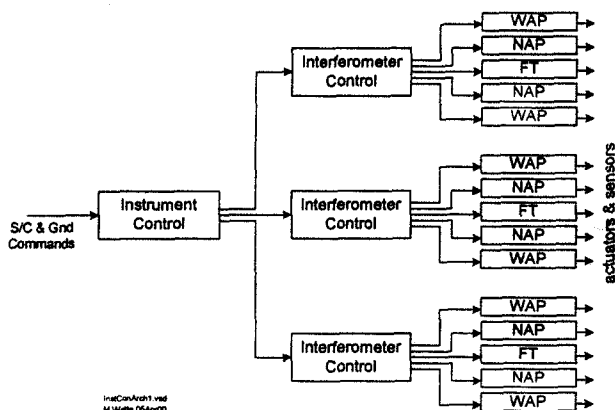


Figure 3. Instrument Control Architecture

The Instrument Control Function dictates the behavior of the three interferometers via commands to the three instances of the Interferometer Control Function. Each of the interferometers (two guides and one science) has direct control over the lowest level closed-loop control servo functions: wide angle pointing (WAP), narrow angle pointing (NAP) and fringe tracking (FT). We will address each of these functions in the following paragraphs.

### 3.1 Instrument Control Function

The Instrument Control Function will exhibit behavior similar to the state diagram in Figure 4. The Instrument will start the sequence from the IDLE state. The initial command will cause the system to the SLEWING state where mirrors and delay lines will be moved to known positions. When the positions have been achieved and the spacecraft is pointed the Instrument will transition to the ACQ\_GUIDES state where fringes will be acquired on the guide interferometers. Once this is done the system will transition to the ACQ\_SCIENCE state where it will acquire science fringes, and then to the HOLDING\_SCIENCE state where fringe data will be sampled on the guide and science interferometer until the requested integration time has been covered.

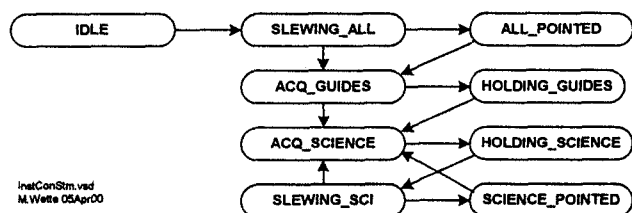


Figure 4. Instrument Control State Machine

Clearly, not all the behavior required to operate the instrument is represented here. What this state machine has given us is an initial design point to start flowing design and requirements to lower levels in the system.

### 3.2 Interferometer Control Function

The Interferometer Control Function will behave like the state machine shown in Figure 5. This state machine must implement the logic for acquiring tracking on the pointing system followed by fringe tracking.

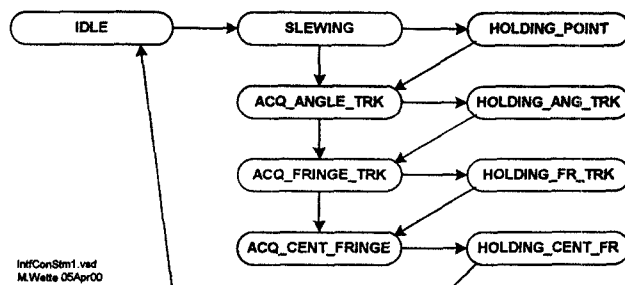


Figure 5. Interferometer Control State Machine

Initial transition from IDLE to SLEWING will be commanded by the Instrument Control Function. After slewing is complete the system will transition to the open-loop HOLDING\_POINT state until commanded by the Instrument Control Function. There will be the capability to have the Interferometer Control Function autonomously transition through the state machine. After pointing has been completed and the Interferometer has been commanded to start acquisition transition to the ACQ\_ANGLE\_TRK state will occur. In this state the interferometer will acquire and center the target star, first on a closed-loop wide angle pointing system (the front end), and then on a closed-loop narrow angle pointing system (the back end). Once closed-loop pointing is tracking on both systems, transition to a ACQ\_FRINGE\_TRK state will occur where the interferometer will acquire fringes. Once fringes are acquired, the interferometer will transition to the ACQ\_CENT\_FRINGE state to find the central fringe. Once the central fringe is found and stabilized, the interferometer is locked.

Of course, closed-loop pointing lock is required for fringe acquisition and tracking so loss of pointing on any of the pointing control systems will likely cause fringe tracking to fail and the system will have to reacquire pointing. There are current efforts in the interferometry programs at JPL to address issue like these in the area of fault tolerance.

### 3.3 Control Servos

At the lowest level of control are the closed-loop control servos. These are developed by the control system analysts and must exist in the framework to be developed by the software engineers. We have developed a spreadsheet for specification of attributes for each servo. The servos covered are the following:

1. WAP, or Wide Angle Pointing. This servo is responsible for controlling the siderostat mirror to

acquire and track the required star on a camera in the siderostat bay.

2. NAP, or Narrow Angle Pointing. This servo is responsible for controlling a fast steering mirror in the siderostat bay to keep the star image centered on an angle tracking camera located in the beam combiner.
3. FT, or Fringe Tracking. This servo is responsible for controlling the delay lines (with three stages of actuation) in order to acquire and track the central fringe.

These servos must work in many states (e.g., idle, acquisition, tracking). For each servo we are tracking the following information for each state in which the servo will operate:

1. the set of measurements needed for the servo and the rates at which those measurements must be sampled,
2. the set of controls (or control commands) for the servo and the rate at which those commands are being output.
3. the set of inputs from other software functions and the rates at which they will be read.
4. the set of outputs to other software functions and the rates at which they will be output.
5. the algorithms which will be executed in that state. These might include different acquisition or tracking algorithms to be design by control system analysts.

Further work to be performed, before detailed design and implementation can begin, includes defining the transitions between the different states in the servos. In addition the latency requirements for scheduling the servos must be determined. See [2] for a discussion of the latency requirements.

## 4 Conclusion

The flight system on SIM includes a instrument real-time control system which will have a high level of complexity and high demands on performance. This type of design requires a thorough analysis and design to achieve its goals. We have illustrated in this paper the process for achieving a workable design framework through systematic analysis.

## 5 Acknowledgements

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## 6 References

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- [2] Walker, W. J., "High Speed Interconnect for the Space Interferometry Mission," 2001 IEEE Aerospace Conference, Mar 2001.

## 7 Bibliography

Dr. Matt Wette is a Senior Engineer at the Jet Propulsion Laboratory, the Guidance and Control Analysis Group. His interests are in control system design, real-time systems, and discrete event control. Matt has contributed to several projects in the development of real-time simulation testbeds. He is currently working on pathlength control and several software testbeds on SIM.

## 8 Appendix

### Science Observation Activity Diagram

TileActDiag1b.vsd

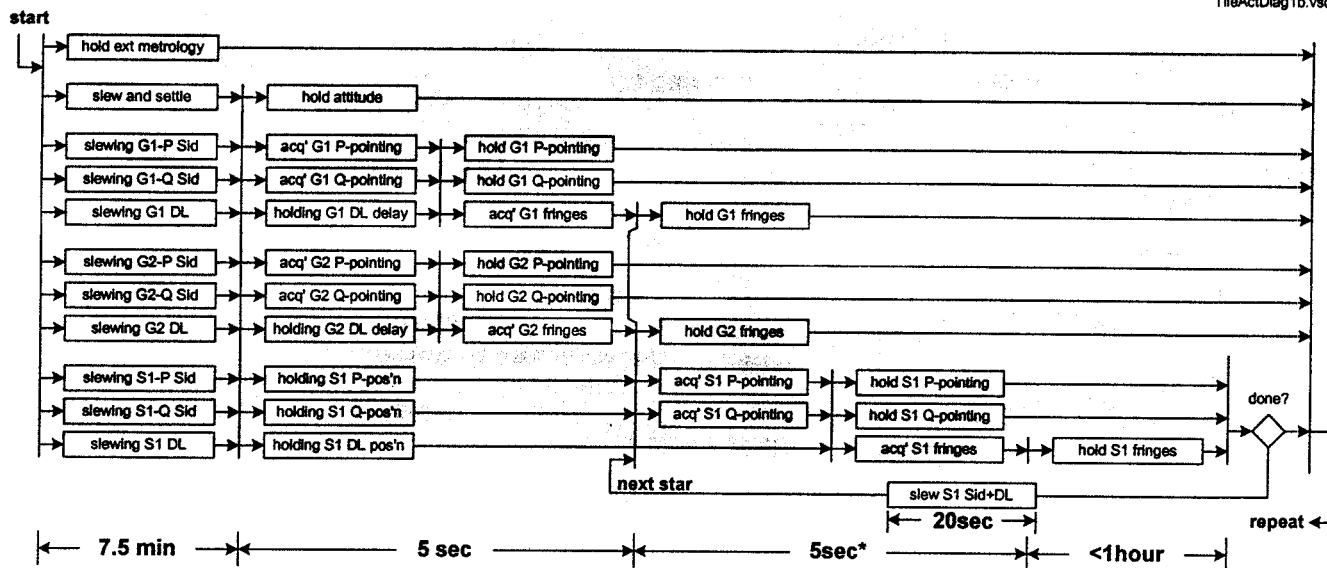


Figure 6. Tile Observation Activity Diagram